Objectives and Metrics in Decision Support for Urban Resilience

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ABSTRACT: A holistic framework for the representation of systems resilience in the context of decision support on societal developments at urban, national and global scales is presented with emphasis on the identification of objectives and corresponding metrics of systems resilience performances in the context of technical, social and environmental systems. The proposed framework facilitates for inclusion of specific policies and stakeholder interests that might be relevant as boundary conditions for the ranking of decision alternatives. The application of the proposed framework and metrics is illustrated through a principal example considering an interconnected system comprised by the subsystems infrastructure, governance and environment. It is shown how decision alternatives for the management of urban systems can be related to societal welfare and capacity to cope with disturbances in the long run and thereby facilitating a systems resilience optimization.

1. INTRODUCTION

The modeling and assessment of systems resilience has gained increased interest over the past 1-2 decades. Based on the foundational works by Pimm (1984) and Holling (1996) significant new ideas and developments have been identified and brought further in the quest of defining, understanding, modeling, and analyzing resilience of systems. Initially the concept of systems resilience, and the related research works, mostly addresses ecological or socio-ecological systems. In the recent decades, however, the research is targeting more directly the interconnected systems enveloping human welfare at local, community, regional and global scales, including in addition to socio-ecological systems, critical infrastructure and built environment systems.

Significant achievements have been made with respect to the understanding of how societal systems interact, how they may be exposed to and perform with respect to disturbances of different types and how they may be adequately designed and managed. There is however still, considerable way ahead before a fully holistic, consistent and applicable appreciation of systems resilience can be established. Challenges yet to overcome include the identification of robust frameworks and metrics for the representation of human welfare, which allows for an adequate consideration of important interrelations and dependencies between society, individuals, technology and the qualities of the environment.

In the present paper, we take up this challenge. Building upon a recent framework for resilience modeling and quantification (Faber et al. (2016) and Faber (2018)), the societal performance with respect to preparedness, response and recovery in case of disturbances is addressed in a novel long-term perspective of societal developments.

Section 2 starts out with a discussion on the role and adequacy of decision analysis in support of societal developments. Thereafter, in Section 3 objectives of resilience management and relevant metrics of systems performance characteristics are identified and outlined. In Section 4, a framework is presented and discussed which accounts for the identified objectives and metrics and supports decision making with respect to resilience management of systems at urban, national and global scales. Finally, the application of the framework is illustrated with a principal example in Section 5.

2. ON DECISION ANALYSIS FOR SOCIETY

Planning, implementing, measuring, directing, and adapting resilient societal developments at urban, national and global scales is generally appreciated to comprise decision problems subject to significant uncertainty. In the following, considering resilience at urban scales, resilience and sustainability is addressed jointly.

2.1. Decision analysis for resilient developments

As suggested in Faber et al. (2017) and Faber (2019), Bayesian decision analysis lends itself as a theoretical framework to support decisions in pursuit of resilient and sustainable developments. The formalism, as outlined in Fischhoff (2015), is relatively straight forward. Given that adequate models are available to i) represent the preferences of the decision maker through a utility function and ii) to select and map decision alternatives into expected value of utility, decision analysis is reduced to what could be termed an exercise of systematic and consistent information management. However, the tasks associated with i) and ii) are generally not trivial, for a range of reasons. One important reason is that the selection and mapping of decision alternatives onto expected value of utility necessitates a rather deep and specialized understanding of the context of the decision analysis, e.g. how technical systems perform individually, interact mutually as well as how they perform jointly with socio-ecological systems.

In practical applications of decision analysis indeed much emphasis is directed on these aspects. However, Fischhoff (2015) concludes by underlining that the tasks associated with i) are absolutely key for the usefulness of decision analysis as a means for decision support. The representation of the preferences of the decision maker and their mapping into utility determine in a fundamental manner the objectives, which are represented in a subsequent ranking of decision alternatives. This may as clearly shown by e.g. Tversky and Kahnemenn (1981), be realized to comprise a highly ethical problem for the utilization decision analysis as an instrument to guide societal developments. The framing of decision problems strongly affects the preferences of decision makers, stakeholders, the identification and selection of relevant decision alternatives and the associated valuation of the possible outcomes of these.

Sen (1985) contributes to the discourse on ethical and economic decision making by introducing the concepts of “functionings” and “capability” for individuals, and underlines that not solely revealed preferences but rather the process of informing preferences is of central importance: In Murhy and Gardoni (2006) and Gardoni and Murphy (2010) the concept of capabilities is introduced in the context of risk management and as a means to direct and measure resilient developments.

In the quest of pursuing decision support for implementation of what in the political scene is declared to be frameworks for resilient societal developments, we take the perspective that the right questions are not known a-priori but must be identified successively in an informed and transparent process. Directions on resilient societal developments must be set based on preferences and available knowledge, but preferences and knowledge should be continuously assessed and directions adapted accordingly. Here it is advocated that this process is best supported by knowledge consistent assessments on how possible decision alternatives, including policies, affect resilience, sustainability and welfare.

3. OBJECTIVES AND METRICS IN RESILIENCE MANAGEMENT

Appreciating that resilience of societal systems at urban scale depends on sustainability at Earth scale – and that the two concepts, resilience and sustainability indeed merge at Earth scale (see Faber (2018)), the following identification and discussion of objectives and metrics will address both of these system characteristics jointly.

3.1. On societal preferences for welfare

A large variety of propositions have been put forward on how to measure, assess and plan for sustainable societal development. Mainstream measures of sustainability and sustainable development stemming from academia include ecological footprint accounting, based on the concept of carrying capacity from population biology (Rees 1992, Wackernagel 1994); (environmental) life cycle assessment developed continuously from the 1960s to present as an aggregate measure of the environmental performance of products and services throughout their lifecycle; and most recently, just over the past decade - social life cycle assessment as an aggregate measure of the positive and negative socio-economic impacts along the life cycle of a product. For industry such measures include environmental social governance reporting, triple bottom line reporting, and corporate social responsibility reporting. By far and large, the most widespread approach to measuring sustainability is through developing and monitoring composite metrics and indices. Since the adoption of The Human Development Index by the United Nations in 1990 as a benchmark indicator of societal development at the nation state level, the number of indices put together by policy-supporting research institutions has grown to include the Environmental Sustainability Index, (see Esty et al. 2005), the Environmental Performance Index (Wendling et al. 2018), and a number of proxy indicators for sustainability, based on the shared assumption that the GDP is not an adequate indicator of growth and development, e.g. the Genuine Progress Indicator (Cobb et al. 1995), and the Happy Planet Index (Marks et al. 2006). Most recently, based on the ideas of Sen (1985, 1999), the concepts of inclusive wealth and inclusive growth have emerged (Kakwani and Pernia 2000, Dasgupta and Mäler 2000, Ali and Son 2007, Ianchovichina and Lundstrom 2009, Klassen 2010, McKinley 2010) resulting in the adoption by the UN in 2012 of the Inclusive Wealth Index (Arrow et al. 2012) as an index for monitoring sustainable societal developments. The IWI is composed of three terms: human capital, natural capital and manufactured capital, together with their respective shadow prices. The shadow pricing concept is introduced to reflect the degree to which societal developments at present depend on resources which are exhaustible.

Inclusive growth in a similar manner as inclusive wealth aims to reflect the prospects associated with societal development and does this by means of accounting for the social equity characteristics of policies for societal development. In this manner, not only expected value improvements of societal developments, in terms of e.g., life expectancy, safety, education and income but also their distribution over the population are accounted for.

In common for the aforementioned measures and indicators is that these are merely representations or models of societal developments, which aim to reflect high-level political objectives. They reflect stated societal preferences at policy level with respect to both the end objective and the path to get there. At the present time, there is however no scientific basis for assuming that these preferences are or will ever be observable at behavioral level in society, i.e. as revealed preferences.

Nathwani et al. (1997) formulated the Life Quality Index (LQI) as a representation of societal preferences for tradeoffs between life expectancy, time spent at work vs leisure and economy (GDP per capita) invested into improvement of health. The philosophical background of the LQI builds on the fact that the only asset and resource available for individuals to spend is time. As quoted in Rackwitz (2002) from the book "Walden" written by David Thoreau in 1852: "The cost of a thing is the amount of what I will call life which is required to be exchanged for it, immediately or in the long run." Both Nathwani et al. (2009) and Ditlevsen and Friis-Hansen (2009), on the basis of this philosophical insight reformulated the LQI based tradeoff between investments into life safety and resulting life safety improvements, into pure time formulations, expressing that the time spent at labor to improve life safety should not exceed the gain in leisure time at good health.

The approach taken here is to measure, assess and direct long-term societal performance through the Life Quality Index (LQI). The LQI is a relative utility function which facilitates a representation of societal welfare developments in dependency of the services and life safety provided by technology, the services provided by the qualities of the environment and the back-couplings which exist between these interconnected systems.

Rackwitz (2002) verified the LQI empirically and in Faber and Virguez-Rodriguez (2011) it is shown that 71 nation states in the World (corresponding to 70% of the global population) develop in accordance with the LQI. Thereby the LQI as opposed to the IWI can be understood to comprise a revealed preference for societal developments at aggregate level.

In the modeling of societal developments we take the perspective that the LQI could comprise an adequate utility function for representing the objective. With this utility, decision analysis provides a means for ranking decision alternatives at policy level in the context of resilience management. Following the approach outlined in Faber et al. (2017), the development of the LQI as a function of economic developments can be modeled with given demographical characteristics such as the GDP per capita, life expectancy at birth and the ratio of time spent for work. Based on the LQI concept it is possible to assess the marginal life saving costs, (see e.g. Faber and Maes (2010), i.e. the costs which should and can be afforded by society to invest into life saving activities.

3.2. On the representation of the environment

All the foregoing considerations take basis in the assumption that human activities predominantly have local, and only minor or even negligible global implications for the living conditions of humans. The capacity of the Earth system to provide adequate living conditions for humans is not accounted for. However, during especially the last decade significant progress in research on the capacities of the Earth system with respect to anthropogenic influences has been achieved. In Rockström et al. (2009) and Steffen et al. (2015) the concept of Planetary Boundaries has been proposed and quantified for characteristics such as atmospheric CO_2 concentrations, bio-diversity, fresh water and phosphor. Substantial uncertainties still prevail in these quantifications but the scientific basis has been established for assessing limits for human activities with impacts on the environment. The concept of Planetary Boundaries may be realized to provide a strong instrument in the context of optimizing strategies for societal developments and for assessing tradeoffs between welfare, resilience and sustainability.

Thus to account for physical limits to anthropologic effects on the Earth system we propose to use the concept of Planetary Boundaries and to assess policies for societal developments in terms of their associated likelihood or probability that the Planetary Boundaries, i.e. the capacities of the Earth Life Support System, are exceeded; the principle is illustrated in Figure 1.

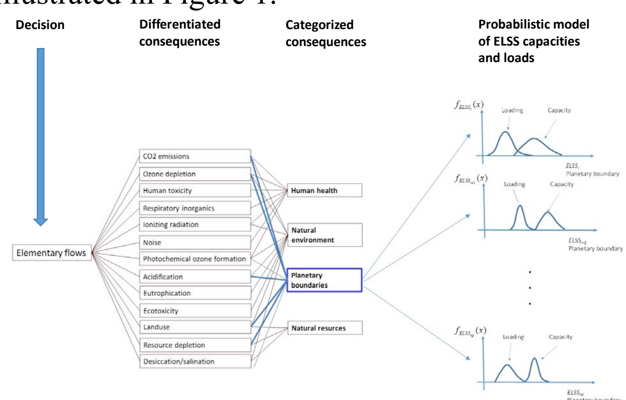


Figure 1 Proposed approach for representing the effect of decisions with respect to resilience management on sustainability.

To take benefit of the concept of Planetary Boundaries two aspects must be considered, namely the quantification of the capacities of the individual Planetary Boundaries and the loading on the individual Planetary Boundaries. The modeling of the capacities is surely a task of natural scientists, however the modeling of the loading side appears to be a task of engineers. Following Faber (2018) and Faber et al. (2017)

any decision in the context of resilience management related to use of materials can be assessed with respect to its associated elementary flow, assessed through Life Cycle Assessment (LCA). In addition, health and safety risks caused by accidents and failures following the decision may be assessed based on probabilistic risk analysis, see e.g. JCSS (2008). The elementary flows and risks may finally be categorized into impacts affecting health, environment, Planetary Boundaries and natural resources.

3.3. Urban scale objectives for resilience and sustainability

To account for political preferences for sustainable societal developments as well as possible specific preferences of stakeholders, e.g. at urban scale, we propose to assess the paths of feasible or optimal policies in accordance with the IWI and the IG. Moreover, we propose to utilize the concept of resilience as a measure of appropriateness and stability of local societal developments and to assess and measure resilience performance at policy level through the associated likelihood or probability that local societal developments exhaust local capacities with respect to environment, human capacity and economy. Finally, it is highlighted that any requirement, such as fulfillment of local regulations and stakeholder preferences, can be accounted for as boundary conditions for the optimization of the LQI.

4. RESILIENCE MODELING FRAMEWORK

As highlighted in the foregoing, the concepts of resilient and sustainable societal developments may be understood as being constructs of contemporary stated preferences with respect to different possible future evolutions of society at local and global scales. Whereas the overlying objectives of resilient and sustainable societal developments are relatively clear, it is less clear how i) such objectives can be operationalized and ii) how different possible policies aiming to reach the objective, and their associated societal development paths, may be compared and benchmarked.

4.1. Organizational systems

To cast light on these issues it is informative to relate the concepts of risk, resilience and sustainability to the context of societal decision making. Figure 2 provides an illustration of how societies at different scales and distributed geographically are hierarchically interconnected at different organizational levels. For the purpose of simplicity the lowest level of representation in the illustration is chosen at municipality level. Further detailing may be introduced depending on the need for resolution in a given context to ensure e.g. appropriate representation of the systems comprised of local communities, livelihoods, ecosystems, qualities of the environment together with specific types and objects of infrastructures and their mutual interdependencies.

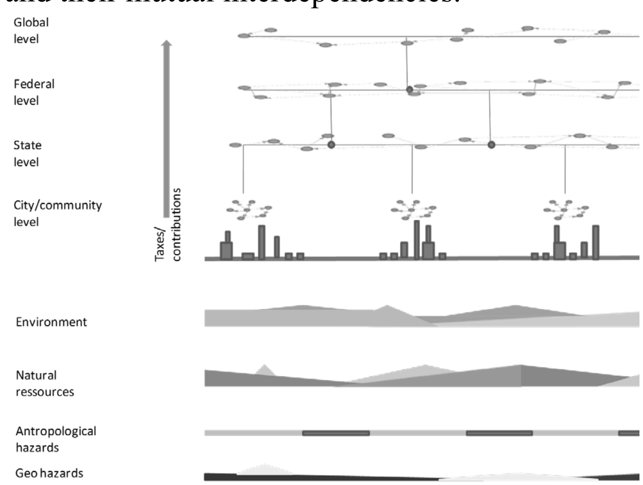


Figure 2 Societal organization and geographical constraints. Adapted from Faber et al. (2017).

The main purpose of Figure 2 is to highlight that societal systems at different organizational levels interact with each other and with the boundary conditions provided by nature. Nation states, regions, municipalities and communities are connected by governance structures. Different levels in the organizational hierarchy have different roles and responsibilities in the overall governance system and depending on the particulars of the governance system they share natural resources, income and risks.

Traditionally, at a given level in the societal organizational hierarchy the main emphasis is directed on the management of risks, in the sense of reducing the expected value of losses and damages associated with geo-hazards and anthropological hazards. Such losses may typically relate to safety and health of people, but also to the qualities of the environments, loss of production, reduction or loss of infrastructure services as well as associated monetary expenditures and lost income.

Figure 3 shows that societies, due to differences in geographical location, are subject to different geographical boundary conditions for what concerns at least three main aspects, namely available natural resources, environmental conditions and geo-hazards. Anthropological hazards may, as suggested in Figure 2, also differ over geography, but such differences may to a large degree be explained by the other mentioned geographical boundary conditions. Risk management at different geographical locations for this reason often has significantly different foci. Moreover, due to differences in availability of natural resources and environmental conditions also the livelihoods vary substantially over geography. Indeed the mentioned differences to a large extent may be considered covariates in the context of understanding why the economy in some nation states appears to be under developed; such nation states may in most cases be realized to be geographically challenged rather than anything else.

Risk management at the different individual levels of societal organization is a strong instrument for decision support on societal developments but as risk management is implemented in practice, by means of regulations, standards and codes, it generally fails to capture important system effects. Interdependencies, and cascading failures within and between different systems such as infrastructure systems, ecological systems and social systems are often neglected or overly simplified.

4.2. Interlinked systems and resilience failure

The concept of resilience addresses these interdependencies and directs focus on the ability of the combined system in the face of disturbance events caused by geo-hazards or anthropological hazards to maintain services and functionalities over time – without any support from the outside of the considered combined system, see also Figure 3 and Figure 4.

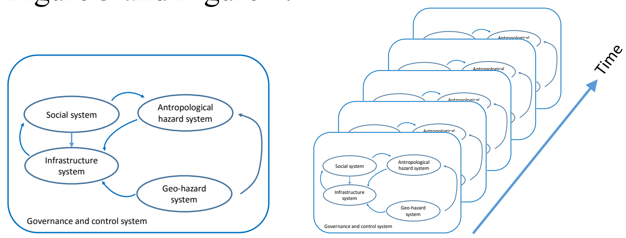


Figure 3 Illustration of interconnected systems which must be accounted for in resilience modeling. Adapted from Faber (Routledge, 2019).

Figure 3 illustrates an interlinked system comprised of a social system, an infrastructure system, together with geo-hazard and anthropological hazards systems, imbedded and managed in regulatory and monitoring systems.

In Figure 4 the principle of resilience failure from Faber et al. (2017) is illustrated. Resilience failure for an interlinked system takes place when one or more of the vital capacities of the system are exhausted. Such capacities may relate to the economic capacity, human capacity availability of vital resources like fresh water, food etc.

As illustrated in Figure 4 the capacities of a system may be represented and modelled in dependency of the services provided by the system. The modeling of this relationship is crucial for the modeling of resilience failure. Following the discussion of sustainability and Planetary Boundaries from Section 3.2 it is readily realized that events of sustainability failure may be modeled in the exact same manner as events of resilience failure.

Appreciating that there are significant uncertainties associated with the modeling of capacities as well as loadings both in the case of resilience modeling and sustainability modeling it follows that events of both types of failure are most adequately modeled and assessed probabilistically, see also Faber et al. (2017) and Faber et al. (2018).

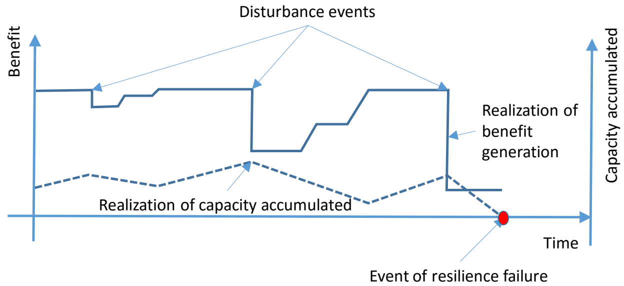


Figure 4 One realization of the benefit and capacity generation – as well as a resilience failure event for a system subject to disturbances.

4.3. Tradeoffs in resilience management

Based on the foregoing propositions on the representation of resilience of urban systems in the context of societal decision support for resilient and sustainable societal developments, it is instructive to assess the possible insights which may be derived on a purely qualitative basis. In the following we will focus on the tradeoffs between welfare, resilience and sustainability.

An urban system is considered represented by an infrastructure system providing basis for economic growth (GDP) and contributions to welfare (LQI). The infrastructure system is subject to disturbance events which may lead to loss of services and events of resilience failure over time. The management options for the infrastructure system are represented through different decision alternatives p. In Figure 5 the decision alternatives are ordered along the x-axis in accordance with reducing probability of resilience failure $P_{RF}(p)$.

Assuming that improvements of resilience performance of the infrastructure system are associated with use of more material and more costs – and accounting for uncertainties and random characteristics of the resilience and sustainability performances of the infrastructure system, it may be assumed that the expected value of the contributions to GDP, i.e. $E[\Delta GDP(p)]$ will follow the general trend of the curve shown in Figure 5.

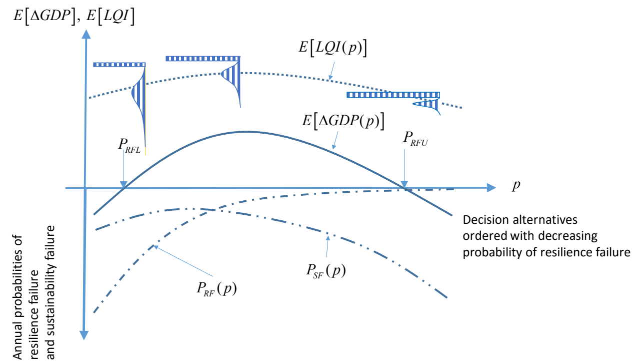


Figure 5 Illustration of tradeoffs between resilience, welfare and sustainability.

For systems with very poor resilience performance, $\Delta GDP(p)$ will be low and maybe even negative even if the cost of such systems is small due to repeated losses caused by disturbances. As the resilience performance is increased it can be expected that also $\Delta GDP(p)$ increases – until a point where the costs associated with increasing resilience performance over weighs the benefits associated with the high resilience performance. Since the LQI depends on the GDP it may be assumed that the expected value of the LQI, i.e. $E[LQI(p)]$ and the GDP follow the same trend as a function of p.

In Figure 5 the general characteristics of probability density function of $LQI(p)$ are shown on top of the $E[LQI(p)]$ curve. It may be expected that for low resilience performance the variance of the resilience is high and vice versa. The same applies of course for the variance of $\Delta GDP(p)$. Finally, the probability of sustainability failure may be expected to follow the curve $P_{SF}(p)$. For systems with poor resilience performance it may be expected that repeated failures of the infrastructure system will lead to increased material consumption. Increasing resilience performances will reduce the probability of sustainability failure – to a certain point where the use of material required to achieve further resilience performance improvements exceeds the use of material needed to restore the infrastructure system after disturbances. From the qualitative assessment of the tradeoffs between resilience, welfare and sustainability it is apparent that resilience management must be undertaken with care to achieve the optimal balance.

Finally, based on the general characteristics observed from Figure 5 the trends of time evolutions of welfare (LQI) illustrated in Figure 6 may be anticipated. If the system is managed such that the probability of resilience failure P_{RF} satisfies $P_{RFU} \geq P_{RF} \geq P_{RFL}$ (see Figure 5) the welfare (LQI) will develop positively. If P_{RF} is outside this interval welfare will develop negatively.

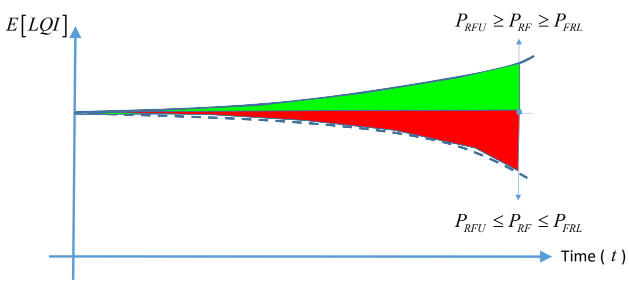


Figure 6 Trends of welfare development as function of infrastructure resilience performance.

5. PRINCIPAL EXAMPLE

The present example takes basis in the infrastructure system also considered in Faber et al. (2018) where details on the applied modeling may be found. The infrastructure system is represented through a Daniels system with 100-year service life and n_C constituents, see Figure 7.

Here we investigate the economic growth (ΔGDP), contributions to welfare (LQI) and the resilience of the system, subject to four selected decision alternatives namely the;

a. number of constituents n_C,
b. design requirements in terms of constituent reliability represented by the variable z_1,
c. preparedness level and
d. percentage of annual benefit $\chi\%$ which is saved for financing of future potential economic expenditures, e.g. repair and replacement activities after future disturbance events.

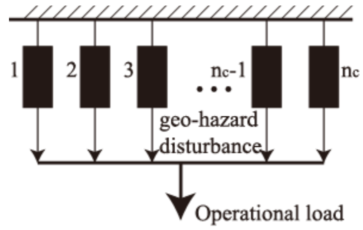
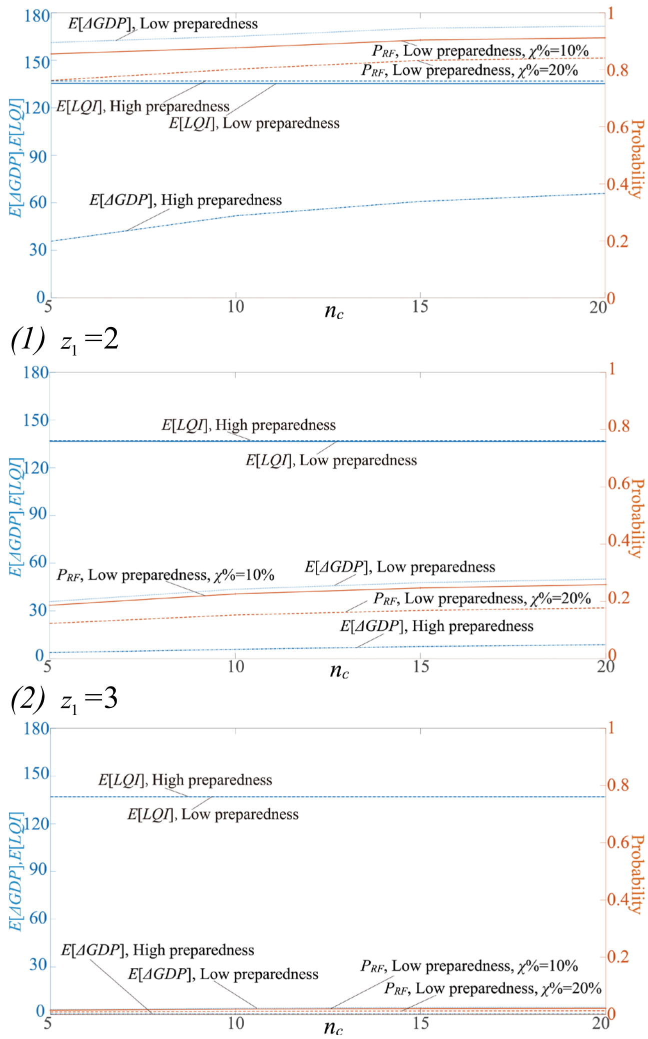


Figure 7 Illustration of the infrastructure system represented through a Daniels system.



(1) $z_1 = 2$

(2) $z_1 = 3$

(3) $z_1 = 4$

Figure 8 Illustration of $E[\Delta GDP]$, $E[LQI]$ *and* P_{RF} *for the system subject to different scenarios.*

These decision alternatives represent governance decisions with respect to infrastructure, government, regulatory and social systems respectively. Three different values of z_1 are considered, corresponding to different target annual probabilities of constituent failure, from approximately 10^{-1} to 10^{-4}. The results from 10^{6} numerical simulations are provided in Figure 8.

It is seen that the contribution to the development of GDP i.e. $E[\Delta GDP]$ reduces for the case of high preparedness level and for small design target levels of failure probability. Also the increase of the number of constituents increases $E[\Delta GDP]$ moderately.

The $E[LQI]$ is not sensitive with respect to variation of n_C , but increases with the preparedness level. As the design target level of failure probability becomes low (z_1 is large), the effect of preparedness level on $E[LQI]$ is also small. The probability of resilience failure, P_{RF} gradually decreases with decreasing levels of the design target annual failure probability. The same applies to the increase of the percentage $\chi\%$ and the preparedness level. The probability of resilience failure for systems with high preparedness level and high percentage $\chi\%$ is always close to zero, and not shown in the figures.

6. DISCUSSION AND CONCLUSIONS

A framework together with objectives and metrics have been formulated which facilitates governance of resilience of societal systems of a certain size such as urban habitats. The framework builds on the idea that systems will fail to be resilient if their vital capacities are exhausted and they need help from the outside to recover from disturbances. Sustainability at Earth scale is identified to comprise a necessary condition for resilience of systems at any scale – and the two notions indeed merge at Earth scale. Based on the proposed framework it is possible to quantify resilience and sustainability in probabilistic terms, and decisions may be assessed relative to their effects on the probability of resilience and sustainability failure, respectively. In the governance of resilience of systems at urban scales, it is proposed to optimize decisions on societal developments based on the Life Quality Index; the only societal preference for the tradeoffs between expenditures and health improvements which has been empirically verified so far. Optimization of societal developments based on the LQI should however be undertaken subject to fulfillment of in principle any policies and/or stakeholder preferences for the distribution of welfare as well as possible inconveniences over the population. Moreover, any decision made must conform with regulations and standards at local scales – which is also facilitated by the proposed framework by imposing such requirements through constraints on the optimization of welfare. It is found that there are rather significant tradeoffs between welfare, resilience and sustainability. Welfare and sustainability may be at stake both if too little or too much is invested into resilience improvements. It is imperative that more knowledge is established to quantify and assess these tradeoffs for the enhancement of resilient and sustainable developments.

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